Early views on binocular rivalry

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Contributions from 19th Century scholars to binocular rivalry research are well recognized, however, observations concerning the phenomenon commenced centuries earlier and suggest a rich seam of research that is much less well known. This chapter discusses these early investigations, along with conflicting views and observations thereafter. We also discuss the early application of notions of attention and consciousness to rivalry. Such notions have more recently been the subject of concerted investigation into distinguishing brain activity mediating the rivaling states from that underlying visual stimulation. Observations in the literature that preceded this key principle are discussed. We also trace the rivalry studies that followed and note their relevance to current thinking on the phenomenon.

Introduction

> The sensations of the senses are tokens for our consciousness, it being left to our intelligence to learn to comprehend their meaning.
> (Helmholtz, 1925, p. 533)

Our experience of the world, as mediated by the senses, is stable and unitary. That is, we are conscious of a single and stable external world. This occurs despite the fact that our bodies and body parts move relative to the world and our sense organs are paired. It is this latter aspect of unitary visual experience, mediated by spatially displaced eyes, that we will examine. Indeed, appreciating the existence of binocular rivalry has its origins in departures from singleness of vision. For example, Aristotle discussed binocular single vision, but it tended to be in the context of its breakdown (diplopia) either by distorting one eye or in strabismus. More than two thousand years later, the inventor of the stereoscope, Charles

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Wheatstone, wrote: “No question relating to vision has been so much debated as the cause of the single appearance of objects seen by both eyes” (Wheatstone, 1838, p. 387). He also examined binocular rivalry using the stereoscope. A paradox in the history of research on binocularity is that rivalry was examined experimentally before the involvement of retinal disparity in depth perception was demonstrated (by Wheatstone). Nor was the stereoscope the first binocular instrument, but the earlier ones were enlisted to examine the experience of rivalry rather than depth.

Binocular vision in antiquity

In binocularity we find one of the supremely psychological phenomena of vision, hence the constant interest that has been given to it since antiquity. There are many aspects to binocularity including the pathways from the two eyes to the brain, the combination of colors and contours, binocular rivalry, eye movements as well as binocular single and double vision. Binocular single vision has been discussed at least since the time of Aristotle.

Aristotle did discuss binocular single vision, but it tended to be in the context of its breakdown (double vision). He described one of the most common ways of inducing double vision – by gently pushing one eye with the finger. Singleness of vision with two eyes has been examined experimentally since Ptolemy (Smith, 1996), who defined lines of visual correspondence for the two eyes. The concept is probably embodied in the mythological cyclops who forged thunderbolts for Zeus, and in the Homeric *Odyssey*, where cyclops was a one-eyed giant. The location of the single eye was central in the forehead, and the locus of binocular visual direction is now referred to as the cyclopean eye. Ptolemy effectively defined the plane of binocular singleness as passing through the fixation point and perpendicular to the common axis. This was repeated by Galen (May, 1968), Ibn al-Haytham (also known as Alhazen, 1572), and by Aguilonius (1613), who named and defined it as the horopter. On the basis of his observations, Aguilonius proposed that singleness of vision is a consequence of fusion between the corresponding images in each eye.

Theoretical issues have directed, and been derived from, observations on binocular rivalry, eye dominance, and strabismus, and comparisons between tasks performed with one or two eyes similarly conflate observation and theory. As with many other aspects of visual perception, binocularity has been analyzed in terms of phenomenology and optics.

Over two thousand years ago, Euclid examined binocular vision with the consistency that he had adopted for other aspects of spatial vision – it could be reduced to optical projections. In fact, his discussion of the projections from two eyes was rather cursory, being restricted to three different sizes of sphere with respect to the interocular distance. During the 2nd Century A.D. the situation was transformed by Ptolemy in optics, and by Galen in ophthalmology. The difference between Euclid and Ptolemy is marked, and the latter can be considered as paving the way for modern approaches to binocular vision (see Howard & Rogers, 2012; Howard & Wade, 1996; Wade & Ono, 2012). Ptolemy carried out controlled observations of the perceived locations of vertical cylinders; from these he specified the conditions for singleness of vision, the distinction between crossed and uncrossed disparities, and the direction in which objects are seen with two eyes. Remarkably little was added to Ptolemy's analysis until the 17th Century; it was extended somewhat by Ibn al-Haytham who profited considerably from a thorough knowledge of Ptolemy's work. Ptolemy probably influenced his near contemporary, Galen, who pursued similar lines of enquiry. Galen took Ptolemy's demonstrations into the real world: rather than viewing cylinders arranged on a board, Galen looked at cylinders, or columns, laid out before him.

The essence of investigating binocular vision was distilled from the methods adopted for stimulating the two eyes. An ancient technique involved fixating on one object located further from the eyes than another. This method was introduced by Ptolemy, and elaborated by Ibn al-Haytham, before its widespread adoption in the 17th and 18th Centuries. Another technique involved placing a septum between the eyes, so that peripheral objects could be seen by one eye but not the other, a method described by Galen.

Ptolemy appreciated that monocular and binocular visual directions were not necessarily the same. In order to confirm this empirically, he constructed a board on which he could place vertical rods at different distances in the midline. There followed a description of one of the most commonly used examples of crossed and uncrossed visual directions: with fixation on the far rod, the nearer one appeared double, and to the left with the right eye and to the right with the left eye; the reverse occurred with fixation on the nearer rod. Essentially the same demonstration is now more frequently made with two fingers, rather than rods, held at different distances from the eyes. Ptolemy stated that singleness of vision with two eyes occurred when the two visual directions corresponded, thus introducing the concept of correspondence into binocular vision. He modified his board to take three rods, in the manner that is shown in the accompanying diagram (Figure 1), and found that objects appeared single to two eyes when they were in the same plane as the fixation point. These facts were interpreted in terms of the visual axes and the common axis. Ibn al-Haytham made a similar board on which he placed wax cylinders, but of different colors.

The notion of rivalry between the two eyes was given empirical support by Giambattista della Porta (1593) in his book *De Refractione*. When considering

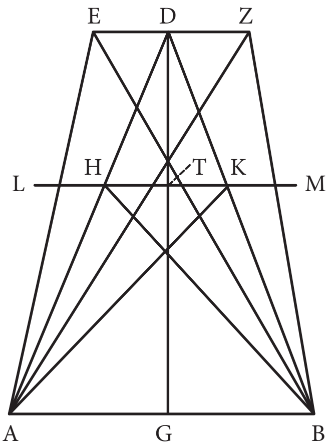

Figure 1. Ptolemy's board for studying binocular vision; the eyes were located at A and B. He wrote: "If we join lines *ae*, *az, zb, eb, ta, tb, bh, ak*, any of *e*, *d*, and *z* will appear in one location, since *ad* and *bd* are the visual axes, and the visual lines which converge on *e* and *z* are corresponding visual lines because *ae* corresponds to *be* and *az* corresponds to *bz*. But *h* and *k*, will appear in one location *t*, since *ah* and *bk* are visual axes. Because *bh* and *ak* are non-corresponding visual lines *h* and *k* will appear at points *l* and *m*: Because visual lines *at* and *bt* are non-corresponding, point *t* will appear in two locations *h, k*." (Lejeune, 1956, pp. 104–105)

singleness of vision with two eyes, he adopted the theory that we only use one at once, and this could be simply demonstrated:

> Nature has given us two eyes, one on the right and the other on the left, so that if we are to see something on the right we use the right eye, and on the left the left eye. It follows that we always see with one eye, even if we think both are open and that we see with both. We may prove it by these arguments: To separate the two eyes, let us place a book before the right eye and read it; then someone shows another book to the left eye, it is impossible to read it or even see the pages, unless for a short moment of time the power of seeing is taken from the right eye and borrowed by the left. (Porta, 1593, pp. 142–143)

Porta's view became known as suppression theory, and suppression is now known not to be restricted to an eye but can operate within parts of the eyes. The contrary view, that we fuse or combine the images from each eye, was proposed soon after by Aguilonius. Since the early 17th Century, the study of binocular vision has often been seen as a contrast, even a conflict, between suppression and fusion theories. Although Porta applied suppression theory to spatial vision, experimental studies from the 18th Century were generally concerned with color rather than contour rivalry.

Binocular color rivalry: From color mixture to perceptual grouping

The combination of different colors presented to corresponding regions of each retina became an issue of theoretical importance following Isaac Newton's (1704) experiments on color mixing: are colors combined by either eye as they are when selected from the spectrum? It was Jean Théophile Desaguliers (1716), an advocate of Newtonian optics, who was amongst the first to draw attention to the phenomenon of color rivalry. He applied a method of binocular combination that became widely employed in other studies of binocular vision, namely, placing an aperture in such a position that two adjacent objects were in the optical axes of each eye (Figure 2). In particular, he showed that dichoptically presented colored lights, or patches of color, rival rather than combine as in Newton's experiments on color mixing.

Desaguliers' method was applied by John Taylor (1738), who added the refinement of placing colored glasses in front of candle flames; he found that colors combined rather than engaged in rivalry. Etienne-François Du Tour (1760) provided a clear description of binocular color rivalry. He achieved dichoptic combination by another means: he placed a board between his eyes and attached blue and yellow fabric in equivalent positions on each side, or the fabric was placed in front of the fixation point (Figure 3). When he converged his eyes to look at them they did not mix but alternated in color. That is, his visual awareness fluctuated between the colors presented to the two eyes.

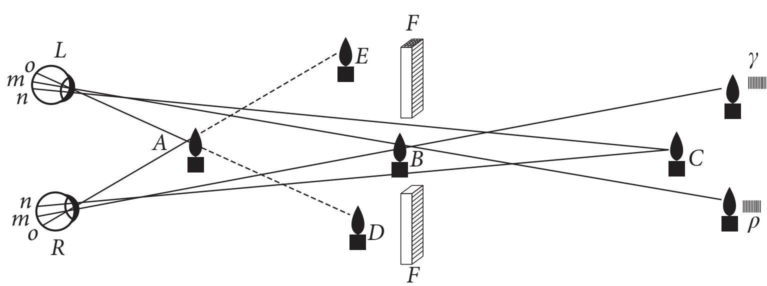

Figure 2. Desagulier's (1716) diagram illustrating how different stimuli could be presented to corresponding parts of each eye: "But if instead of the Candles, ρ be a piece of red Silk, and γ a piece of green Silk, the same Position of the Eyes will make the Image at *B*, appearing like a red and green Spot together without a Mixture of Colours. If ρ be a red hot Iron, and γ a Candle of Sulphur, the Phænomenon will be more distinct." (Desaguliers, 1716, p. 451)

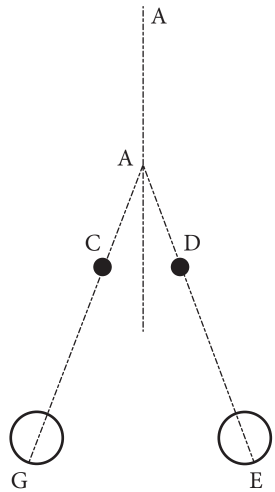

Figure 3. Du Tour's (1760) method of combining colored patches in order to examine rivalry. He wrote: "I glued a round patch of blue taffeta of about an inch in diameter onto one side of a sheet of cardboard, and on the opposite side, another patch of yellow taffeta of the same size, so that the two were exactly back to back. I placed the cardboard against my nose in a vertical plane and perpendicular to my face. Through my right eye I saw the blue patch and not the yellow, and vice versa for my left eye. Thus each one of the two patches formed separate images; blue in my right eye, yellow in my left eye. However, I was aware of only one patch. If that awareness was the result of the simultaneous combination of two images, should not the patch have seemed to be green? Now I was unable to discern the least tint of green. That single patch I saw sometimes appeared blue, sometimes yellow, apparently according to the rays of light from one or the other patches striking my eyes with more energy. Also, sometimes the patch appeared partly blue and yellow.… If one looks with both eyes at a point *A*, four or six inches away, and places on the optical axes *EA*, *GA*, short of the point *A* and their intersection, two small pieces of taffeta, one blue at *D*, the other yellow at *C*, one sees only a single spot of blue or yellow or a combination of colours, and never green." (pp. 514–515)

Du Tour argued that with slight differences in curvature between the eyes, rather than achieving complete fusion, one of the presented colors (or objects) projected more clearly to one eye at a given time than the other color to the second eye. During simultaneous presentation, the two different impressions on the retinas would meet in the brain where the optic nerves came together. He proposed that the more distinct impression then affected the mind and became visible, whereas the other less clearly defined impression would not have such an effect or did not draw the mind's attention. He also argued, in keeping with the suppression theory, that during simultaneous presentation of two different colors, the eyes acted in alternation to see one and then the other image. Such alternate and intermittent action of the two eyes was to avoid fatigue in both simultaneously, through inhibiting one eye while the other eye viewed the presented object.

Du Tour also applied the method of observing the colors through an aperture, as adopted by Desaguliers, and obtained the same outcome. A similar technique was applied by Giovanni Battista Venturi (1802), who compared the combination of sounds to two ears with that of colors presented to different eyes (see Wade & Ono, 2005). He placed blue and yellow papers next to one another on a table and over-converged his eyes to combine them: "I have repeated this experiment often and with care, and I have never experienced a third colour from the two overlapping colours" (translated from Venturi, 1802, p. 389). This was taken to be evidence that the nerves from the two eyes do not combine in the brain.

Yet another technique was to view different colored objects through two long tubes, one in each optic axis. This method was used by Thomas Reid (1764), and he saw the colors combined, although his description was not without its ambiguity: the colors were not only said to be combined, but also one "spread over the other, without hiding it" (p. 326). That is, a single color was not seen, which was also the conclusion of William Charles Wells (1792), Charles Bell (1803) and Ernst Heinrich Weber (1834). Wells amplified this by noting that one or other color was dominant during this 'transparent' phase. Haldat (1806) reported that differently colored liquids placed in prisms before each eye appeared as an intermediate color.

The complexity of the binocular percepts is evident from Johannes Müller's (1838) account: sometimes one or the other color will predominate, whereas at other times "nebulous spots" of one color are visible on the other. Fechner (1861) examined rivalry with colored glasses and with the stereoscope and noted the importance of attention in the alternations that occurred. He also pointed to the similarities of the processes involved in binocular and binaural combination (see Wade & Deutsch, 2008; Wade & Ono, 2005).

One of the problems associated with most of the techniques described above is that the observer needed to uncouple accommodation from convergence. Wheatstone dispensed with these difficulties by viewing different colors with the stereoscope. The outcome was binocular rivalry, but this was either of the whole monocular stimulus or local parts of the two colored discs:

> If a blue disc be presented to the right eye and a yellow disc to the corresponding part of the left eye, instead of a green disc which would appear if these two colours had mingled before their arrival at a single eye, the mind will perceive the two colours distinctly one or the other alternately predominating either partially or wholly over the disc. (Wheatstone, 1838, pp. 386–387)

Thus, Wheatstone was describing the fluctuations in the visibility of the different colors while no changes took place in the colors themselves. The changes in visual awareness corresponded to his inferential theory of vision in which binocularity was considered to be cognitive rather than physiological. Hermann Helmholtz followed Wheatstone theoretically (as is evident from the quotation at the head of this chapter) and he also embraced color rivalry as evidence in its favor. His antagonist, Ewald Hering (1861), argued for a physiological interpretation of rivalry and much of the dispute surrounded the visibility of yellow from dichoptic combinations of red and green. Hering did establish a number of stimulus parameters that influenced rivalry: small color patches yielded more clear-cut rivalry and brief stimulus presentation favored combination rather than competition.

In the early 1860s, binocular rivalry with color images was also investigated by Joseph Towne, a medical sculptor at Guy's Hospital with an interest in binocular vision. In particular, he first sought to understand the relationship between corresponding retinal areas during rivalry using complementary stimulus pairs. Color pairings were introduced to the complementary stimuli. With vertically split discs, the outer semicircle viewed by each eye was the same color while the inner semicircles were another color. When red and black were used (Figure 4a), the colors combined and alternations were not observed. With blue and yellow however (Figure 4b), he observed interocular grouping during binocular rivalry, or stimulus rivalry:

> In the next experiment, the two temporal halves of the retinæ are submitted to yellow, while the two nasal halves are submitted to blue; these colours being disharmonic, it follows that disharmonic colours fall on corresponding parts of the two retinæ, the result being that the colours antagonise, first one, then the other being seen, with now or then an iridescent appearance over the whole field, occasioned by the gleaming of one colour over the surface of the other colour. The disturbance occasioned by this means is sometimes very striking; the four halves of the retinæ appear to be thrown into separate action, so that their respective images are brought together, but not united; and for a second they appear as if struggling, so to speak, for their respective places. Under these circumstances, the changes which occur are remarkable; at one moment there will be a complete disc of yellow, the blue being altogether lost; at the next the yellow will entirely disappear over exactly one half of the disc, so that the resultant image is one half yellow, the other half blue, then the reverse, and so on, with constant alternations.
> (Towne, 1863, p. 121)

With the observations gained from such stimulus presentation, Towne acknowledged the essential utility provided by the stereoscope in their demonstration. In further experimentation, one eye viewed an image of a star composed of yellow

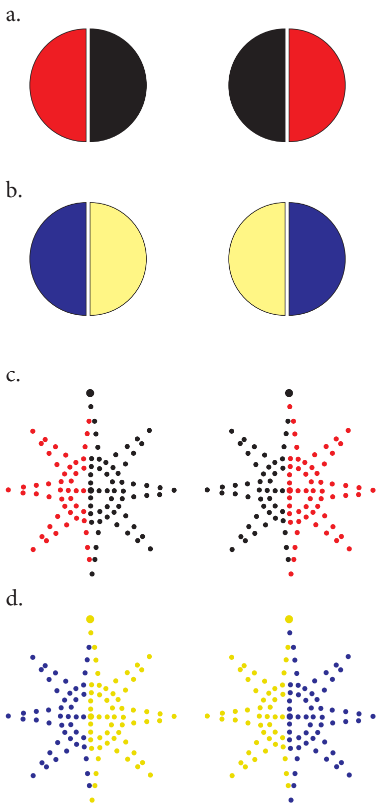

Figure 4. Color stimuli used by Towne to study corresponding retinal areas during binocular rivalry. **(a)** The two discs are "so arranged that the different colours fall upon *corresponding* parts of the two retinæ; *red and black harmonize*, *and the two co-mingle*" while in **(b)**, "[t]hese colours *do not harmonize*; the result is *antagonism* of the two impressions, and that the colours *do not mingle*" (figures reprinted from Towne, 1863, Plate II). **(c)** "These are figures of stars in which identical points of the retinæ are simultaneously submitted to harmonic colours. The blending of the two colours may be observed by comparing the spots that form the *star* with the larger spot, which, when viewed in the stereoscope, appears over the resultant image" (figure reprinted from Towne, 1864; Plate, Fig. 1). When these stimuli were viewed dichoptically, a single stable star of a black-red color mixture was observed. In contrast, perceptual alternations occurred with their blue and yellow counterpart **(d)**, which were not depicted in Towne's (1864) paper and have been illustrated here based on **(c)**.

dots in one vertically symmetrical half and blue dots in the remaining half, while the other eye viewed the complementary image (Figure 4d). What ensued was concurrent binocular combination and rivalry between local zones (i.e., piecemeal rivalry), rather than regular alternations between global coherent percepts as might be expected from his previous observations:

> Over the greater portion of the resultant image, the spots will appear double, the blue and yellow dots lying side by side, while in other parts of the figure there will be constant alternation; *but in no part will the discordant colours blend, or the two images be permanently superposed;* in short, the result may be thus broadly stated – that we have in this instance a double star, or rather a star composed of double rows of spots, excepting where the images occasionally alternate.
>
> (Towne, 1864, pp. 129–130)

Binocular contour rivalry: Conflicting views and philosophical traditions

Binocular single vision occurs when similar images are projected to corresponding parts of each eye. As David Brewster (1844) noted, it can be difficult to distinguish between seeing two similar things and seeing their combination. No such doubts arise about binocular rivalry, which is one of the reasons why suppression theory has been so ardently supported. When dissimilar images are presented to corresponding areas of each eye they do not combine, but compete. Binocular contour rivalry is more clear-cut; the debate has been about whether alternation between the views of each eye occurs rather than whether rivalry exists. In the 2nd Century, Ptolemy arranged stimuli on a board in a manner that would have produced binocular rivalry, but his description of the outcome was ambiguous (see Howard & Wade, 1996; Wade, 1983, 1998).

As noted above, Porta (1593) placed pages of different books before each eye, and stated that the right eye was dominant. Porta was not in a position to relate his observations to functioning within the visual system because he did not have an adequate understanding of the optics of the eye. This was provided a decade later by Johannes Kepler (1604), who described how images are brought to a focus on the eye. The 17th Century heralded the scientific renaissance. The scientific methods that had proved so successful in the physical and chemical sciences were seen as relevant to life processes. The anatomy of the senses and the brain were gradually elucidated, and these anatomical structures were related to function. In vision, Christoph Scheiner (1619) integrated Kepler's dioptrics with an accurate description of the gross anatomy of the mammalian eye. Thereafter, phenomena like binocular single vision could be related to the optics and anatomy of the eye. In addition, the lessons of science were absorbed into philosophy. René Descartes

(1637, 1664) did distinguish between the mechanical body and the immaterial mind, but his application of scientific rigor to understanding the senses set psychology on a course from which it has seldom wavered. His analysis of binocular vision posited its singleness in a singular organ in the brain, the pineal body. Corresponding points on each retina projected to the same locations on the pineal body, thus defining single vision (see Figure 5, left). The spur to studying binocular vision by his opponents was to attack this theory. For example, Sébastien Le Clerc (1679) argued that retinal disparity would not yield single vision:

> Monsieur Descartes having considered that according to his principles external objects should make an impression on both eyes, and that the soul nevertheless had only one perception believed that the images of the same object found in the two eyes are reunited in the brain; but if this great genius had reflected a little more on the demonstrations which he gave in his Treatise on Man, he would have recognised that the images in the two eyes although produced by the same object, are different, and because of these differences their reunion is impossible.
> (Le Clerc, 1679, pp. 44–46)

Le Clerc provided clear diagrams of retinal disparities but he did not see the link between disparities and depth; rather he used disparities to disparage Descartes' theory. Le Clerc (1712) went on to examine binocular rivalry, adopting the method of over-convergence to present different figures to each eye, and remarked that alternation took place. Du Tour (1761) held a prism in front of one eye, and produced the clearest early description of contour rivalry: either the stimulus presented to one or the other eye would be visible, or some mixture of the two views would present itself.

> If one applies a prism held vertically before one of the eyes, so only refracted rays of light are passed to that eye, and with the other eye open, it is certain that different objects will be projected on corresponding portions of the two retinas…. sometimes I would see only objects projected in the bare eye, sometimes only those in the eye covered by the prism, and sometimes the objects projected in one would seem to me to intermingle with the objects projected in the other.
> (Du Tour, 1761, p. 500)

Descartes relied on Andreas Vesalius (1543) for his visual anatomy, whereas Newton performed his own dissections, although they were not published. He alluded to these in Query XV of his *Opticks* where he asked whether the fibers from corresponding regions of each eye were united before they reached the brain, adding a telling reflection on species differences in the visual pathways to the brain. In fact, he had carried out experiments on optic nerves around 1682 but he did not publish details of them; his notes were later printed by Joseph Harris (1775) and Brewster (1855). Newton conducted experiments on optic nerves; he

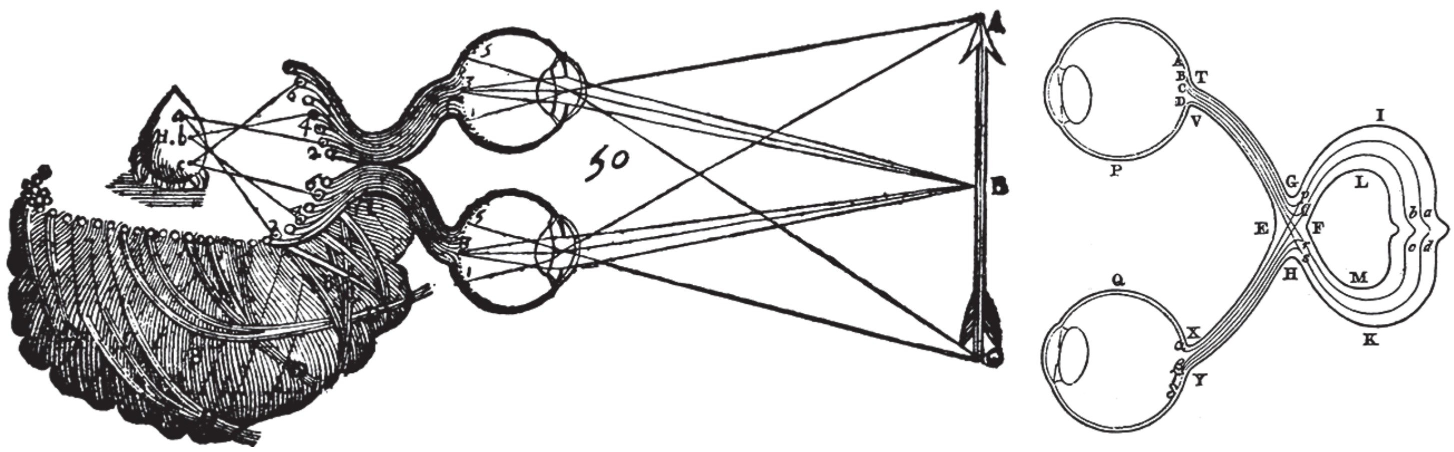

Figure 5. Left, Descartes' (1664) diagram of the visual pathways, with union of corresponding fibers in the pineal body: "the spirits that tend to enter each of the tubules *2, 4, 6*, and the like do not come indifferently from all points on the surface of the gland *H* but each from a particular point; those that come from point *a* of this surface, for example, tend to enter tube *2*, those from points *b* and *c* tend to enter tubes *4* and *6*, and so on. As a result, at the same instant that the orifices of these tubes enlarge, the spirits begin to leave the facing surfaces of the gland more freely and rapidly than they otherwise would. And [suppose] that just as [*a*] the different ways in which tubes *2, 4*, and *6* are opened trace on the internal surface of the brain a figure corresponding to that of object *ABC*, so [*b*] [the different ways] in which the spirits leave the points *a, b*, and *c* trace that figure on the surface of this gland" (Hall, 1972, p. 85). Right, Newton's pathways (from a diagram in Brewster, 1855) displaying partial decussation. He wrote: "though one thing may appear in two places by distorting the eyes, yet two things cannot appear in one place. If the picture of one thing fall upon A, and another upon *α* [its corresponding point in the other eye], they may both proceed to *p* [in the optic chiasm], but no farther; they cannot both be carried on the same pipes *pa* into the brain; that which is strongest or most helped by phantasy will there prevail, and blot out the other" (Harris, 1775, p. 110).

made the first representation of partial decussation at the optic chiasm (shown in Figure 5, right), and proposed a theory of binocular single vision based upon it. Thus, Newton's anatomy specified that rivalry would result from stimulating corresponding points with different stimuli.

Thus, there were experimental philosophers, like Newton, who wished to remain in contact with the phenomena they examined. For them observation and experiment provided the bedrock of science. Newton did not desire to entertain hypotheses – principles that could not be supported by experiment. Rationalist philosophers, like Descartes, were not so constrained, although he did add to the mechanistic approach in a multitude of ways. The anatomy of the senses received benefits from both shades of philosopher, and this was clearly displayed in binocular vision. Both Descartes and Newton brought their brilliance to bear on binocular combination. However, they took the nerves in different directions. Descartes combined them in the pineal body, sacrificing anatomy to philosophy. Newton observed and experimented on the pathways from eyes to the brain, or sensorium, where the signals coalesced. Neither could be confident in their conclusions because so little was known about nerves and their central connections.

While there is no doubt about Descartes' central role in early views on binocular vision and consciousness, it was not until two centuries later that the notion of consciousness was applied specifically to binocular rivalry. In the late 17th Century the term 'consciousness' had become well established in English philosophy writings, while its German counterpart 'Bewusstsein' entered the European lexicon a few decades thereafter (see Palaia, 2012). Further attacks on Descartes' rationalist philosophy issued from Newton's friend, John Locke (1690), who was a leading proponent of British empiricism (or sensism). Locke maintained that knowledge and understanding was acquired only through sensory experience. Therefore, rejecting a distinction between sensory perception and consciousness, it was considered that

> …perception and consciousness are one and the same thing, though they have two distinct names. As far as one looks at this operation as an impression in the mind, one can keep the term perception; as far as one is aware of it, one can call it consciousness. (Jaucourt, 1753; translated in Palaia, 2012, p. 303)

The empiricist tradition was subsequently followed by Wheatstone, Helmholtz and others in examining binocular vision and binocular rivalry. Explicit reference to consciousness however, in writings about rivalry, was not made until the mid-1800s and not considered more widely until the end of that century (see below).

In the 19th Century, psychology emerged as the interface between philosophy and the natural sciences. It addressed the eternal questions of philosophy by deed rather than by word: it embraced the scientific method to frame the questions empirically. The methods adopted initially were adapted from other sciences, most notably from physics and physiology. From the mid-19th Century new methods were developed for studying perception and performance that distinguished psychology from both philosophy and physiology. Nonetheless, the 17th and 18th Centuries did make inroads into the study of the senses, and it is from these that the edifice of 19th Century psychology was erected. Vision provides the lens through which this history can be observed, and it was instruments invented to study vision that transformed psychology into an experimental discipline.

The stereoscope, perhaps more than any other instrument, ushered in the era of experimentation to vision. It is a simple optical device that presents slightly different figures to each eye; if these figures have appropriate horizontal disparities then depth is seen. It could also be adapted to study binocular color or contour rivalry. All the problems with previous devices were removed when radically different shapes are viewed with the aid of a stereoscope (Figure 6). Wheatstone (1838) surrounded two letters by equivalent circles (to ensure binocular alignment) and noted the rivalry that took place. Not only did he describe the alternation, but he also examined a stimulus variable (illumination) that could favor one stimulus over the other:

> If *a* and *b* are each presented at the same time to a different eye, the common border will remain constant, while the letter within it will change alternately from that which would be perceived by the right eye alone to that which would be perceived by the left eye alone. At the moment of change the letter which has just been seen breaks into fragments, while fragments of the letter which is about to appear mingle with them, and are immediately after replaced by the entire letter. It does not appear to be in the power of the will to determine the appearance of either of the letters, but the duration of the appearance seems to depend on causes which are under our control: thus if the two pictures be equally illuminated, the alternations appear in general of equal duration; but if one picture be more illuminated than the other, that which is less so will be perceived during a shorter time.
>
> (Wheatstone, 1838, p. 386)

After Wheatstone's article was translated into German (Wheatstone, 1842), its impact was dramatic. On the one hand, it argued against the prevailing view of single vision advanced by Gerhard Vieth (1818) and Müller (1826), and on the other it presented an empiricist interpretation of binocular vision. It opened up new ways of examining and analyzing combination and competition between the eyes. William James (1890) said that Wheatstone's first paper "contains the germ of all the methods applied since to the study of optical perception" (p. 226). Fourteen years later, Wheatstone (1852) published his second article in which he described and illustrated an adjustable mirror stereoscope, a prism stereoscope,

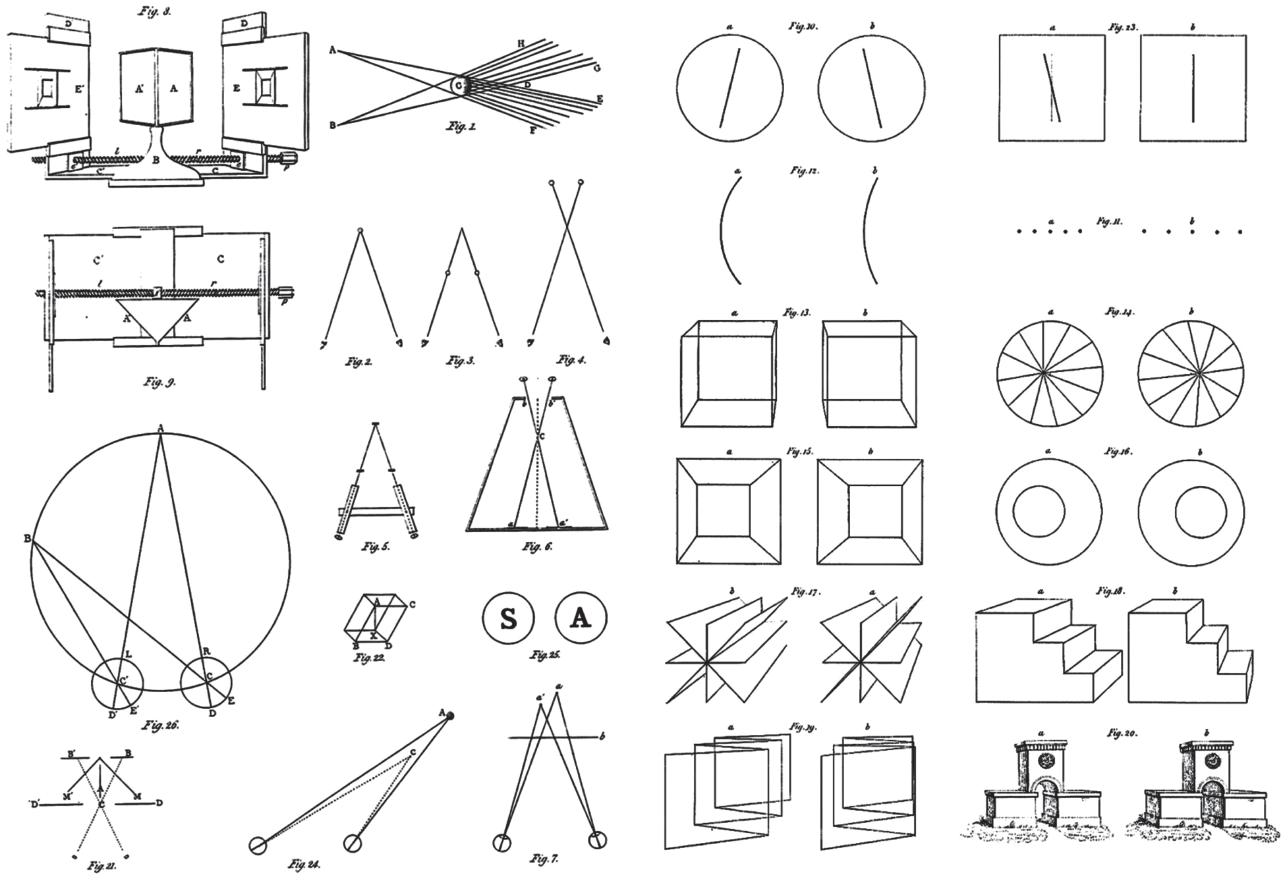

Figure 6. Two plates from Wheatstone (1838) showing the mirror stereoscope and the stimuli he observed with it. Rivalry was examined with Fig. 25 consisting of different letters (S and A) which were presented in equivalent circles, ensuring binocular alignment.

and a pseudoscope for reversing disparities. It was in this article that he drew an explicit distinction between mental and physical philosophy; that is, between psychology and physics, and he placed binocular vision in the province of psychology.

One of those to take up the challenge posed by Wheatstone's work was Peter Ludvig Panum (1858). Not only did he introduce the concept of fusional areas that now bear his name, but he ushered in the stimuli that have been employed more than others for the study of binocular rivalry – orthogonal gratings (Figure 7). He remarked that gratings produced the strongest rivalry and that it was difficult to represent the ensuing changes: occasionally complete gratings were briefly visible but the dynamically varying, mosaic-like composites were seen most of the time. Panum took these to be indices of the physiological processes at play in binocular vision:

> Following the lawful rules that have been stated, the mosaic-like filling of the general visual field, combined with partial fusion of the impressions taking place, arises from neither psychological causes, attention, imagination or the like, nor from any dread of double images, nor from a total alternative paralysis of the two retinas, but from very characteristic means of perception or sensory energies emanating from the simultaneous action of the excitation of corresponding retinal points on the central organ of vision (in the brain).
>
> (Panum, 1858, pp. 93–94)

Panum's fusional areas were seen as a way of salvaging Müller's concept of identical retinal points from Wheatstone's attack on it. One of the first German sensory physiologists to defend Müller's concept was Brücke (1841): he argued that stereoscopic vision occurred as a consequence of directing the visual axes successively to different parts of an object. This was so despite Wheatstone's (1838) description of stereoscopic vision with afterimages, which was confirmed by Dove (1841). Nonetheless, eye movements continued to play an interpretive role in binocular rivalry as did attention. Fechner (1861) considered that rivalry phenomena provided a clear example of attentional shifts, while Wundt (1862) placed more emphasis on eye movements. Wundt stated that the actual basis for rivalry resided in changes in the convergence angle of the eyes. He examined rivalry between vertical and horizontal gratings and supported the eye movement hypothesis by demonstrating that when the vertical grating is physically moved horizontally it becomes dominant, and vice versa. Without physical movement either one or the other grating is visible or a mosaic made up from them can be seen. Wundt introduced a subtle variation on the stimuli used for rivalry: he presented very wide vertical and horizontal stripes but the wide stripes had finer lines of the same orientation within them. When one set of the wide stripes was dominant both the wide and fines lines in the orthogonal orientation disappeared.

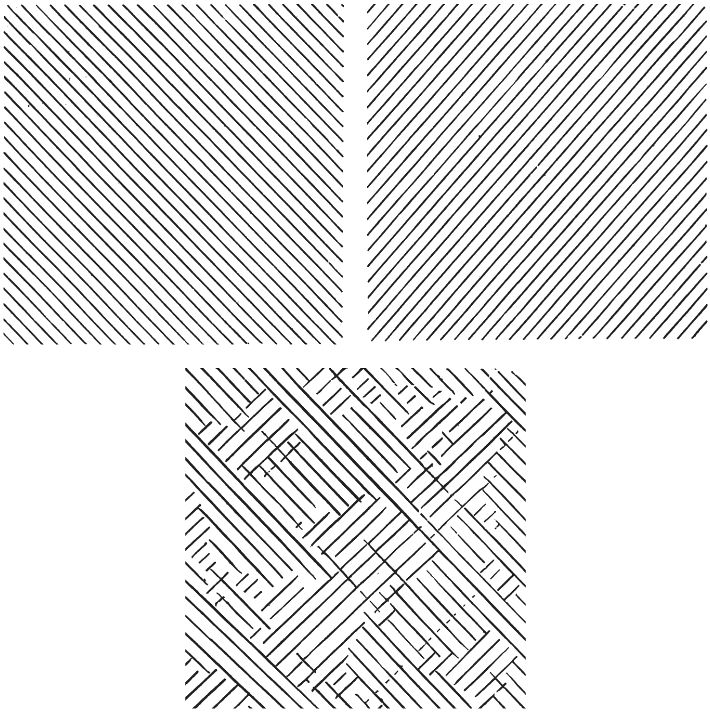

Figure 7. Panum's (1858) diagram of orthogonal gratings presented to contralateral eyes with an impression of their fragmented perception; in addition to intervals during which either grating alone is visible.

Towne (1862a) at the time had also examined binocular contour rivalry. He surmised that the function of the eyes was to receive and transmit images, while that of the mind was to perceive and interpret them. Other stimuli included a vertically split image of a camel or two vertically split discs. With the camel half-images, its front half was presented to the right nasal hemiretina and the rear half to the left nasal hemiretina, yet a whole coherent image of the animal was perceived. The same perceptual outcome occurred when the camel's front and rear halves were presented respectively to left and right temporal hemiretina. Towne concluded that

> …in both examples, the circumstances under which the symmetry of the animal is restored, and note how far these circumstances agree, with what for *convenience*, may be spoken of as the *retinal law* of visual direction…. which rules that the image shall be referred in a direction opposite to the part of the retina affected. (Towne, 1863, p. 117–118)

This initial interpretation would be pursued in subsequent studies on visual direction. Following his four papers on rivalry (Towne, 1862a, 1862b, 1863, 1864), he devoted four other papers to the study of visual direction. This body of work however had remained largely neglected until it was recently brought to light (Wade, Ono, & Mapp, 2006). Thus despite emanating from a defining period in rivalry research, Towne's report of perceptual grouping and stimulus rivalry alternations had otherwise not been recognized. A similar fate had befallen his important role in demonstrating the laws of visual direction (see Ono & Wade, 2012; Wade et al., 2006), which were later credited to Hering despite the fact that Towne acknowledged Wells' earlier work. With the invention of the stereoscope, the perception of depth had become the prevailing experimental and theoretical topic of interest. This instrument of change contributed to Towne's work on visual direction being neglected, though it was the same instrument that also enabled his novel observations on binocular rivalry.

Helmholtz (1867, 1925) was opposed to Panum's analysis of binocular rivalry, as he was to Hering's, because they were physiological rather than psychological. Nonetheless, he did use some of Panum's figures in his *Handbuch*, like two broad black lines, one vertical and the other horizontal, or two thin, orthogonal lines in each eye. Helmholtz also modified the stimuli so that he viewed a grid with one eye and a broad cross with the other, or provided binocular fixation aids in the centers of orthogonal gratings (Figure 8). Helmholtz took great pride in his ability to maintain stable fixation while controlling the location of his attention, and interpreted the pattern of visibility in terms of attentional control:

> These experiments show that man possesses the faculty of perceiving images in each eye separately, without being disturbed by those in the other eye, provided it is possible for him, by some of the methods indicated above, to concentrate his whole attention on the objects in this one field. This is an important fact, because it signifies, that *the content of each separate field comes to consciousness without being fused with that of the other field by means of organic mechanisms*; and that, therefore, *the fusion of the two fields in one common image, when it does occur, is a psychic act*. (Helmholtz, 1925, p. 490)

It is this statement and its implications that were a source of dispute between Helmholtz and Hering (1864), who like Panum (1858), adopted a physiological interpretation of rivalry. Helmholtz's confidence in his ability to maintain stable fixation might have been misplaced. As he himself acknowledged, eye movements, even very small ones, in one direction relative to orthogonal gratings will have differential consequences for the stimulation of the retinas.

Wheatstone can be seen as the link between British empiricist philosophy and Helmholtz. Both were philosophically empiricists and were trained in physics, so that they could adopt the methods of physics to study binocular rivalry and

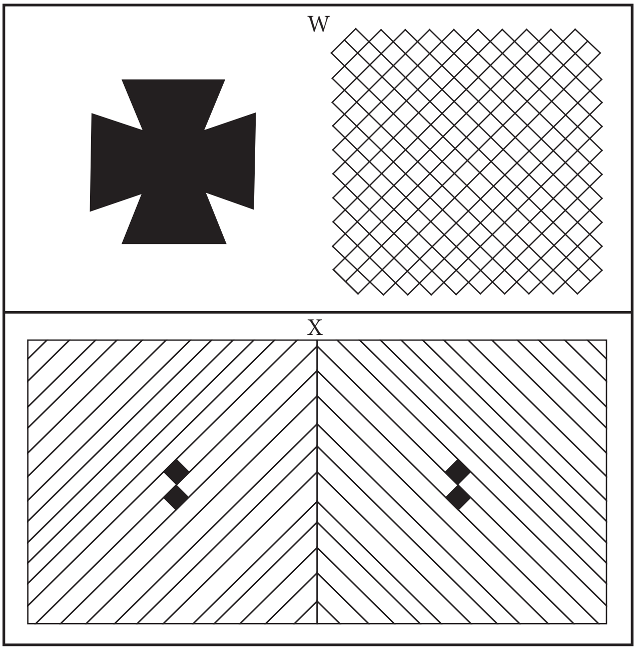

Figure 8. Figures used by Helmholtz (1867, 1925) to study binocular rivalry. With regard to the upper pair of rivalry figures (W) he claimed that "I simply have to count the squares in a row or to compare them to each other and notice whether they are all of one size or whether the lines are perpendicular, etc. As long as I devote my attention to this part of the figure, it stays in sight. On the contrary, the moment I let my attention be distracted to a corner of the cross or to one of its sides, the lines vanish more or less completely, and I see the cross steadily" (Helmholtz, 1925, pp. 496–497). With regard to the lower pair (X) he said that we "generally get the impression of an irregular blending of the two patterns, with one system of lines predominating at some places in the field, and the other system of lines at other places" (p. 497).

interpret it in terms of learning. The contributions made by Helmholtz to visual science are legion, but his most lasting impact was his theory of perception: he followed the empiricist philosophers in arguing that perception is like unconscious problem-solving – making unconscious inferences about the nature of the external world based upon the inadequate information furnished by the senses. Helmholtz appreciated that the process of perception takes place in the brain, following transmission of the neural signals from the sensory receptors – the brain only had indirect access to the external world, via the senses, and it could only process messages in the language of nerve impulses. This realization made any equation of the retinal image with perception unnecessary. By adopting a starkly empiricist interpretation of perception, and by contrasting it so sharply with nativism, he reopened a debate that has reverberated throughout perception research ever since. The debate was personified in the conflict between Helmholtz and Hering, and the main battle-grounds were color vision and stereoscopic depth perception (see Turner, 1994).

The bitter rivalry, both theoretical and personal, between Helmholtz and Hering was matched by an earlier one between Wheatstone and Brewster concerning the nature of binocular combination (Wade, 1983). However, it could be argued that the stereoscope has performed a singular disservice to our understanding of binocular rivalry. As Helmholtz noted, rivalry is a natural consequence of our binocular interactions with the world; it is a resolution of conditions that apply to most of what we see when using two eyes. It occurs when the differences between the images in the two eyes are too large to be combined, and stereoscopic depth cannot be extracted from disparity. When we bifixate on part of an object most of what is projected to the peripheral retinas is too disparate to yield depth; because the peripheral stimuli arise from different depths their retinal images also tend to be out of focus. We are not generally aware of this binocular rivalry as both visual resolution and attention are typically associated with the fixated object rather than peripheral ones. If attention shifts to a peripheral object then the eyes also move to bifixate it. Using stereoscopes, binocular rivalry is rarely examined under these conditions of natural stimulation. It is typically studied with different patterns presented to corresponding foveal regions of the two eyes – as if we are bifixating two different objects. Thus, the conditions under which binocular rivalry is investigated experimentally seldom occur in normal binocular vision. Implications for consciousness studies arise from these considerations if binocular rivalry is taken as some index of its operation. In the following section, we trace the development of conceptual precursors that are now a focus of modern rivalry studies into visual consciousness.

Alternations in attention and consciousness

From the end of the 19th Century, neural theories of consciousness based on rivalry experiments were first put forward by Burtis Burr Breese (1899). Along with examining the effects of motor inhibition on memory, he used binocular rivalry as a paradigm to examine the inhibition of sensations and argued that consciousness had a sensorimotor basis. More importantly, he made the first quantitative measures of binocular rivalry. He examined: (i) the effect of stimulus strength changes (e.g., motion, size, luminance) on perceptual predominance and alternation rate; (ii) individual variation in alternation rate (see also below); (iii) the effect of unilateral motor activity on predominance; (iv) rivalry between after-images and their slower alternation rate compared to real stimuli; and (iv) the phenomenon of monocular rivalry. He also investigated the influence of willpower on binocular rivalry. Subjects could voluntarily hold attention on one image with the (inadvertent) use of eye movements, but without eye movements such voluntary control was limited (see also Blake, 2005).

Breese argued that binocular rivalry could not be explained by purely mental conditions because complete control over the alternations could not be demonstrated. Correspondingly, physical conditions such as retinal adaptation could not solely explain the effect of different brightness levels on rivalry rate, which may have also been due to greater attention directed towards the brighter image. Instead, he concluded that the phenomenon "would be at once 'psychical' and 'physiological' in that it is dependent upon central processes, and is affected by the nature of motor adaptations" (1899, p. 48). Breese subsequently elaborated on the distinction between consciousness and attention during rivalry, along with postulating their associated activity in the brain:

> …in the case of the alternating red and green squares in the stereoscope, if, when I give my attention to the red square, the green square displaces it in sensory consciousness, I may still be thinking about the red square, attending to its quality, size, et cetera, so that the change in consciousness is not a change of attention. What really happens in this case is that part of the time I am attending to the sensory perception of the red square, and part of the time to its memory image. On the other hand, the green square may not occupy clear or attention-consciousness at all… So we infer that the brain activities corresponding to attention-consciousness involve larger areas than those corresponding to mere sensation or perception. We conclude, therefore, that attention may change with the changes of sense-stimuli or may act independently of them. Shifting of the attention involves more factors than those involved in the fluctuation of minimal sensations or in the rivalry of objects presented to the sense-organs. (Breese, 1917, pp. 74–75)

Ten years after his original study, Breese (1909) repeated the rivalry experiments on himself and noted that his alternation rate was almost identical. This within-individual retest reliability of binocular rivalry rate was also reported by others (McDougall, 1906), as was his earlier finding of individual variation in alternation rate (Bose, 1902, 1907). Such variation across different individuals had been found a decade prior by a Scottish eye surgeon, Thomas Reid (1889), who is better known for developing the portable ophthalmometer (Gutmark & Guyton, 2010). The quantitative rivalry experiments conducted by Breese and his interpretation of their findings reflected the broader development of psychology into a scientific discipline. They were also a reflection of increasing knowledge about the brain and interest in the neural basis of attention and consciousness. Both notions of attention and consciousness had been central to early views of the mind, thus not surprisingly the advent of experimental psychology also marked the beginnings of a science of consciousness.

The close relationship between attention and consciousness stemmed from very early notions of levels or degrees of consciousness, that is, the conscious mind and subconscious mind, and their interaction in acquiring new ideas and knowledge. On this basis, Gottfried Leibniz, one of the leading rationalist philosophers of the 17th Century, conceived the notion of 'apperception', which was later developed by Immanuel Kant and Johann Herbart. Apperception was conceptualized as the means by which conscious sense impressions were understood in terms of subconscious prior experience (Pillsbury, 1908; Titchener, 1908).

The notions of apperception and levels of consciousness were taken up by Wundt (1874). He proposed however that while consciousness had levels, these were characterized instead as levels of attention. Attention was therefore considered to have a single focus wherein an object was held in consciousness at any given moment (now commonly understood as selective attention or an attentional spotlight). Meanwhile for objects or events outside this focus, an individual was less aware or not conscious of them. This early notion of attention as an adaptive function and action of the mind became a common explanatory concept in 19th Century continental Europe. For example, binocular rivalry was thought to involve an act of attention (Fechner, 1861; Funke, 1857), before the publication of Helmholtz's third volume of his *Handbuch* and the combined presentation of all three volumes in Gustav Karsten's *Allgemeine Encyklopädie der Physik* in 1867. Others had also considered attention as being involuntary, with binocular rivalry involving alternations in attention rather than alternations in retinal fatigue (Meyer, 1856), or had interpreted the alternations as being due to involuntary avoidance of double images (Brücke, 1841). More broadly, the conceptualization of attention on the Continent was in opposition to the parallel advancement of British associationism, which was reductionist in its approach and considered mind as a passive state.

To understand mental processes and the active mind, Wundt had utilized trained introspection in highly controlled laboratory conditions. This approach was taken on by his student, Edward Bradford Titchener, who instead characterized consciousness by levels of clearness rather than attention. Having originally studied in England, Titchener was also influenced by the ideas of David Hume, another leading advocate of British associationism. After moving to America in the 1890s, Titchener founded structural psychology, which sought to elucidate basic elements of the mind, including the brain basis of mental events. Meanwhile, strong opposition was gathering from functional psychology, which emphasized individual differences and studying the adaptive function of consciousness with both introspective and objective experimental methods. Its main proponent was William James (1890), whose student James Rowland Angell further championed this school of thought. Angell, using ambiguous figures as an example, also proposed a basic mechanism regarding their perception:

> It is clear that a consideration of illusion affords new and striking confirmation of the part played in perception by previous experience. The cortical reaction suggested by the stimulus does not happen to correspond to the object actually present. But this cortical reaction is evidently determined by the impress of old perceptual experiences whose traces have been preserved. The same point is admirably illustrated by such drawings as the accompanying, figures 52 and 53. We can see the [Schröder's] stairs, either as they appear from above, or from below. In one case the surface *a* seems nearer to us; in the other case *b* seems nearer. We can see in the other [Wheatstone] figure a big picture frame, the frustrum of a pyramid, or the entrance to a square tunnel. Yet one and the same object is presented to the retina in each case. The eye can hardly be accused of responsibility for the shifting results. But lines like these have actually been connected in our former perceptions with the several objects named, and in consequence the cortical reaction appropriate to either of them *may* be called out. It would seem abundantly certain, therefore, that while a portion of what we perceive is always supplied from without, another portion, and often the dominant portion, is supplied from within ourselves.
>
> (Angell, 1904, pp. 134–135, bracketed information added)

Angell thus suggested that both neural activity associated with either rivaling image and constructive processes were required to achieve perceptual dominance. This proposal was consistent with the empiricist view of perception, yet he was also highly critical of structural psychology's reductionist approach to consciousness:

> The more extreme and ingenuous conceptions of structural psychology seem to have grown out of an unchastened indulgence in what we may call the 'states of consciousness' doctrine. I take it that this is in reality the contemporary version of Locke's 'idea.' If you adopt as your material for psycho-[l]ogical analysis the isolated 'moment of consciousness,' it is very easy to become so absorbed in determining its constitution as to be rendered somewhat oblivious to its artificial character. (Angell, 1907, p. 64)

While many early 20th Century psychologists discussed consciousness and its investigation in their writings, very few did so specifically in relation to rivalry. Angell was an exception, as was William McDougall. McDougall had a special interest in biology during his undergraduate years, a period when he also researched muscular contraction in Cambridge and at the St Thomas' Hospital physiological laboratory in London headed by Charles Sherrington. As a graduate student he then worked with W. H. R. Rivers, who had been invited to give lectures at Cambridge on the physiology of the sense organs. It was after this period that McDougall developed a keen interest in experimental work on vision, in particular through his opposition to Hering's opponent processing theory (see McDougall, 1911, 1930). In studies using Schröder's staircase and binocular color rivalry, he found similarities in their (successive) interval durations, and in the effect of voluntary control and monocular atropine administration on percept dominance (1901a, 1901b, 1903a, 1906). He also experimented with a bistable rotating windmill illusion, and presented a multi-path hierarchical representation of the nervous system (i.e., spinal and subcortical centers, sensory cortical areas, association areas; McDougall, 1902). From this background, McDougall hypothesized that such phenomena represented

> …a principal condition of the alternating appearance in consciousness of two objects, while the impression made on the sense-organ remains unchanged, is fatigue of the cortical tract concerned in the perception of either object, a fatigue which is induced during the period of perception, and which rapidly passes away during the period of rest in which the other object is present to consciousness. … [T]he paths which suffer fatigue and become alternately active and passive or, in other words, alternately transmit the stream of nervous energy coming in from the sense-organ and cease to transmit it while it is diverted to the alternative path, these paths are, in the case of the binocular rivalry of colours, paths of the sensory area of the cortex, paths of the second level in the scheme…; while in the case of ambiguous figures…the nervous energy coming in from the sense-organ is continuously transmitted by the paths of the sensory level while it penetrates alternately to one or other of two higher-level paths.
>
> (McDougall, 1906, pp. 346–347)

From this passage, it is clear that McDougall provided an early multi-level neurophysiological account of perceptual rivalry (i.e., binocular rivalry, ambiguous figures and bistable motion illusions). This account is also the key forerunner to the principle of neural dissociation that is now common in modern mechanistic studies of rivalry (i.e., distinguishing neural activity mediating the alternate percepts from that corresponding to the constant sensory input).

McDougall's work was the earliest specifically to compare binocular rivalry with other rivalry types, that is, comparing alternating visual phenomena induced by dichoptic and dioptic presentation, respectively. Over fifty years prior to this, similarities had been noted between binocular rivalry and olfactory perceptual alternations with dichorhinic stimulation – presenting a different odor to each nostril (Valentin, 1848). From the end of the 19th Century experimenters further examined such olfactory rivalry (e.g., Henning, 1916; Zwaardemaker, 1895), and also explored the effect of auditory stimulation on binocular color mixture and rivalry predominance (Urbantschitsch, 1903).

Returning to McDougall, his account above regarding visual rivalry was also notable by articulating elements of Gestalt satiation theory which would be formulated decades later. In addition, it has been argued that his conceptualization of both neural fatigue and reciprocal inhibition between neurons (McDougall, 1901b, 1903b) provided a clearer explanation for Sherrington's (1906) finding of rhythmic alternations between antagonistic muscle groups (see Reiss, 1962). McDougall also applied his approach to binocular rivalry, thereby enunciating key aspects of modern reciprocal inhibition models of the phenomenon. Moreover, he first reported observations of another phenomenon closely related to binocular rivalry, now known as flash suppression:

> …if, when a red field is presented to one eye and a blue field to the corresponding area of the other eye, one eye be closed or covered for a brief period – one second will suffice – the colour presented to that eye always predominates over and inhibits the colour presented to the other eye as soon as the eye is uncovered, *i.e.*, the rested tract predominates over the relatively fatigued tract, even if the period of rest be not more than one second. (McDougall, 1901b, p. 598)

Despite the precedence of such observations, there were also detractors of McDougall's inhibition model, along with the utility of rivalry itself: "The whole field of bilateral rivalry is too little known to permit its exploitation as proof of anything except our ignorance" (Dodge, 1926, p. 113). In further experiments he also examined the effects of pharmacological agents on a bistable windmill illusion (McDougall & Smith, 1920), which were followed by other drug studies on ambiguous figures (Ewen, 1931; George, 1936) and binocular rivalry (Bárány & Halldén, 1947; George, 1936).

With the rise of American behaviorism and functionalism early in the 20th Century, there also came increasing criticism of the study of consciousness and attention given their highly subjective nature. Scepticism was similarly directed at the interpretation of empirical work in the light of such notions. This view, coupled with the emergence of rigorous animal behavior studies (e.g., Pavlovian conditioning), lead to the establishment of behaviorism as the prevailing objective scientific approach in psychology – rejecting introspective methods. The dominance of behaviorism was partly reflected in over two decades of waning interest in binocular rivalry, especially outside of Germany. It was considered a subjective phenomenon that could not be examined objectively with the methods available at the time (Lack, 1978). Correspondingly, studies directly comparing binocular rivalry with other rivalry types were rare (e.g., George, 1936; Washburn & Gillette, 1933). In the late 1920s, Margaret Washburn, a former student of Titchener, then conducted a series of studies on ambiguous figures, binocular rivalry and stereoscopic vision until her death in 1939. Based upon that work, she argued for the importance of motor responses in the voluntary control of rivalry and in explanations of consciousness.

Early in the 1940s different types of visual rivalry were used by Louis Thurstone, a former student of Angell, in an exploratory multiple-factor analytic study. The number of rivalry alternations among a battery of other perceptual, motor and cognitive measures were recorded, with the aim of using the perceptual tests as a measure of personality. This aim was based on his hypothesis that "the dynamics of perception, and of other restricted functions, are not isolated and that these several functions are so related that some characteristics of the person as a whole might be inferred from the dynamics of one of these functions" (Thurstone, 1944, p. 3). In addition, it was thought that individual differences in the perceptual measures might reflect a central rather than peripheral parameter associated with an individual's personality. In a small twin study, the number of binocular rivalry alternations was also used among several other measures to explore a genetic (hereditary) basis for differences between identical and fraternal twin pairs (Thurstone, Thurstone, & Strandskov, 1953, 1955; see also chapter by Ngo, Barsdell, Law, & Miller, this volume).

Several years earlier, McDougall (1926) had proposed an association between personality types and ambiguous-figure rivalry. He suggested that extraversion (identified in hysteria and manic-depressives) was associated with a slow rivalry rate, while introversion (identified in neurasthenia and schizophrenia) was associated with a fast rivalry rate. This hypothesis was tested by investigators such as Margaret Washburn, Joy Guilford (also a former student of Titchener), Raymond Cattell and Hans Eysenck (e.g., Cattell, 1933; Cattell & Tiner, 1949; Eysenck, Granger, & Brengelmann, 1957; Eysenck, Holland, & Trouton, 1957; Guilford & Braly, 1931; Washburn, Keeler, & Parshall, 1929). Among other measures, alternation rate was examined as an indicator of personality subtypes and psychiatric disorders (see also chapter by Ngo et al., this volume). The work in particular by Guilford, Cattell and Eysenck, like that of Thurstone, was within the context of psychometrics rather than characterizing rivalry phenomena and their underlying mechanisms.

From the late 1940s onwards, renewed interest in examining attention saw a gradual resurgence in studies of binocular rivalry (Lack, 1978). This work came from three perspectives: (i) using the phenomenon to discern individual differences and intrinsic factors (e.g., personality, learning, motivation, intelligence, semantic value, heredity, pharmacological effects, subliminal perception), (ii) the effect of stimulus manipulations (i.e., extrinsic factors), and (iii) the relationship between binocular rivalry and stereoscopic vision (see also chapter by Klink, van Wezel, & van Ee, this volume). At the end of the 1960s, enquiry from an intrinsic factors perspective began to wane. This decline likely reflected the influence of rigorous neurophysiological studies into mechanisms of retinal disparity processing (Barlow, Blakemore, & Pettigrew, 1967; Hubel & Wiesel, 1962). At the time there was also a shift towards quantitative psychophysical methods to examine binocular rivalry. Other lines of enquiry that developed during this period were the psychophysics of structure-from-motion perception and bistable motion phenomena (Braunstein, 1976; Wallach & O'Connell, 1953), and a cognitive processing approach to studies of ambiguous figures and form perception (e.g., Fisher, 1968; Vickers, 1972). With binocular rivalry, novel experiments conducted by Robert Fox, Paul Whittle and Willem Levelt, for example, revealed further key features of the phenomenon (see Blake, 2005; chapter by Brascamp & Baker, this volume). This body of work, along with human electrophysiological studies of rivalry conducted by others, marked a revival in the field that has continued to flourish ever since.

Summary and conclusions

In historical terms, binocular rivalry has been considered in the context of singleness of vision. For Greek and medieval philosophers it was a problem associated with misalignment of the eyes. In the 16th Century, Porta proposed that it was a solution to binocular single vision as he supposed that only one eye operated at one time – mostly the right eye. From the time of Descartes and Newton singleness of vision was posited in speculative anatomical combinations. French scholars used binocular rivalry to attack Descartes' theory and in the process introduced new methods to examine it. Color rivalry was examined by these methods before contour rivalry was investigated.

In the 19th Century the experimental study of binocular rivalry was transformed by Wheatstone's invention of the stereoscope and contour rivalry was examined in more detail because of its close relationship to stereoscopic depth perception. Factors affecting rivalry, like attention and eye movements, became the focus of theoretical interpretations, and the implications of the phenomenon for consciousness emerged. At the turn of the century, Breese measured the durations of dominance for the stimuli presented to each eye during rivalry, heralding the quantitative era. However, the rise of behaviorism suppressed interest in a phenomenon for which there were no external correlates, despite the investigation into personality and clinical correlates of binocular rivalry and ambiguous figures. The resurgence of studies in the 1960s linked rivalry on the one hand, to the growing knowledge about the neurophysiology of binocular combination, and on the other to similar fluctuating visual phenomena like ambiguous figures and bistable motion illusions. These phenomena and variants like flash suppression are now powerful tools in contemporary research on mechanisms of visual consciousness.

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